

## The CODEX-ESPRESSO experiment: cosmic dynamics, fundamental physics, planets and much more...

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**Summary.** — CODEX, a high resolution, super-stable spectrograph to be fed by the E-ELT, the most powerful telescope ever conceived, will for the first time provide the possibility of directly measuring the change of the expansion rate of the Universe with time and much more, from the variability of fundamental constants to the search for other earths. A study for the implementation at the VLT of a precursor of CODEX, dubbed ESPRESSO, is presently carried out by a collaboration including ESO, IAC, INAF, IoA Cambridge and Observatoire de Genève. The present talk is focused on the cosmological aspects of the experiment.

## 1. – Introduction

Hubble's discovery of the expansion of the Universe, enabled in the late 20s by the new observational facilities on Mount Wilson, brought to an end the cherished belief held by most physicists of the time, including Albert Einstein, that the Universe is static and not evolving.

The discovery has later been impressively confirmed by a vast range of astronomical observations and led to the now widely accepted Hot Big Bang Theory, which rests on firm pillars such as the detection of the relic Cosmic Microwave Background (CMB, [10, 13]) and the experimental verification of the prediction for the synthesis of light elements [1].

The Hot Big Bang is now an essential aspect of the cosmological standard model and the central question has become: *what is the stress-energy tensor of the Universe?*, which - with the ansatz of homogeneity and isotropy - reduces to: *what is the mean density and the equation of state of each mass-energy component of the Universe?* Since these parameters determine both the evolution with time and the geometry of the metric that solves the Einstein equation one can use a measurement of either to infer their values.

The above question has been addressed by various observations: from CMB and SN Type Ia to the abundance of clusters, from weak lensing to the large scale structure traced by galaxies and the inter-galactic medium (IGM), and the results are consistent with the so-called *Concordance Model*, a Friedmann-Robertson-Walker Universe with no curvature, which has provided a first moderate embarrassment, due to a significant component of dark matter whose nature remains elusive, and a major surprise with the discovery that the expansion of the Universe has recently begun accelerating for physical reasons basically unclear at the moment. The latter is accommodated by modifying the stress-energy tensor to include a new component with negative pressure, something reminiscent of the old ether, falsified by the experiment of Michelson and Morley.

It is important to note that the above mentioned experiments (CMB, Lensing, SNIa, etc.) are based on geometry, some of them require a prior on spatial curvature and a detailed understanding of the growth of density perturbations, hence a specific cosmological model. For this reason, measuring the dynamics of the Universe in a clean direct way would be a new fundamental test of General Relativity and Cosmology.

## 2. – Probing the nature of the universal expansion

Is it possible to directly measure the history of the expansion? The goal is to reconstruct the evolution of  $a(t)$ , the scale factor as a function of time. We ordinarily measure  $a(z)$  and to recover the unknown  $a(t)$  we need to know  $da/dt(z)$ . In other words we need to measure the Hubble constant,  $H(z) \equiv \dot{a}/a$  using dynamics.

A way to implement this experiment is to monitor the redshifts of cosmological sources. The change of these redshifts as a function of the observer's time is a direct signal of the acceleration of universe's expansion and hence of its dynamics.

The variation of the redshift as a function of time [5, 4], turns out to be a simple difference between the Hubble constant at the present epoch and the one at the time of the emission

$$(1) \quad \dot{z} = (1 + z) H_o - H(t_e).$$

The practical problem is the smallness of the signal. Fig. 1 shows what is expected for a concordance-like model: we are dealing with accelerations of the order of 1 cm/s/yr!

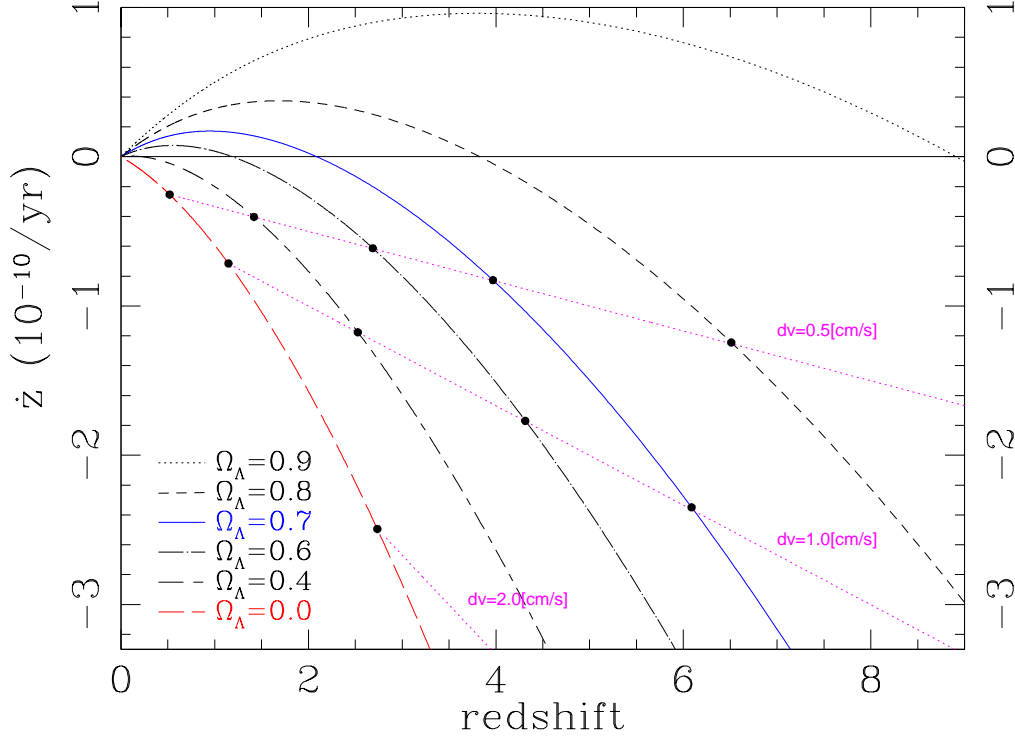


Fig. 1. – Evolution of  $\dot{z}$  as a function of redshift. The cosmological parameters have been fixed to  $\Omega_{tot} = 1$ ,  $H_0 = 70$  and different values of  $\Omega_\Lambda$  have been considered. The lines represent the behavior of the Eq. 1, assuming the observation of the Lyman- $\alpha$  line.

The signal is small but displays a characteristic signature: a pattern of shrinking of the spectrum at high- $z$  and stretching at low- $z$ . This is typical of a non-zero cosmological constant: the zero crossing depends only on the ratio  $\Omega_\Lambda/\Omega_m$  ( $z_o \simeq 2$  in a Concordance Cosmology) and the amplitude on  $H_o$ .

### 3. – Measuring the Cosmic Signal

How to measure this signal? Masers (e.g. [7]) or molecular lines could appear very good candidates: lines are sharp and wavelengths can be measured with very high accuracy, due to their rather long wavelength, noise is also much less of a problem than at optical wavelength. However, these targets turn out not to be well suited, since they typically reside in deep potential wells and are subject to large peculiar accelerations, of the same order or larger than the cosmic signal.

Absorptions from the many intervening lines in front of high- $z$  QSOs are the most promising candidates. Simulations, observations and analysis all concur in indicating that the Lyman forest and associated metal lines are produced by systems sitting in a warm IGM following beautifully the Hubble flow [11].

The idea is then to observe the Lyman forest of a number of QSOs, uniformly distributed all over the sky, today and few years from now, and measure the shrink-

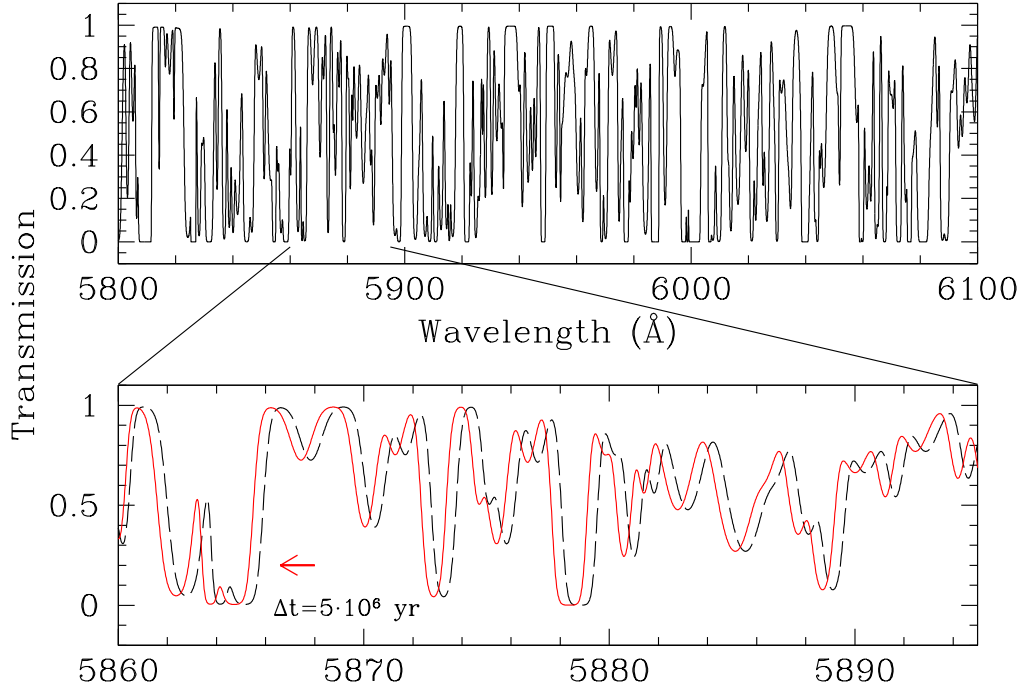


Fig. 2. – Upper panel: the transmission of the intergalactic medium at redshift  $z \sim 4$ , observed along the line of sight to the QSO Q0000-26. The average transmission is about 0.5 and hundreds of features modulate the signal between 0 and 1. Lower panel: the expected shift in the spectral features due to the cosmic deceleration in a time interval of  $5 \cdot 10^6$  yr.

ing/stretching pattern of the absorption features (see Fig. 2). The variation of the normalized transmission is expected to be of the order of  $10^{-6}$  in ten years. Is it feasible?

Difficult as it may be, such an experiment is no more complex, nor more expensive, nor of less fundamental importance than what our colleagues at CERN regularly do.

Accuracies not far from what we need for detecting the cosmic signal are presently being reached in the observations of radial velocity perturbations induced by extra-solar planets (e.g. HARPS [6]). We want to do the same but with objects that are hundred thousand times fainter than the extra-solar planets targets, and on timescales of decades. An extremely large light bucket is needed and in this respect the E-ELT is going to play for European astronomers the role of LHC for particle physicists.

#### 4. – The CODEX Team

On the basis of the conviction enunciated above, the CODEX (COsmic Dynamics EXperiment) team has formed [9]. From the work carried out by the team to explore the feasibility of the experiment [4] we show here the results aimed at quantifying the optimal redshift range and instrumental characteristics. They can be summarized by the

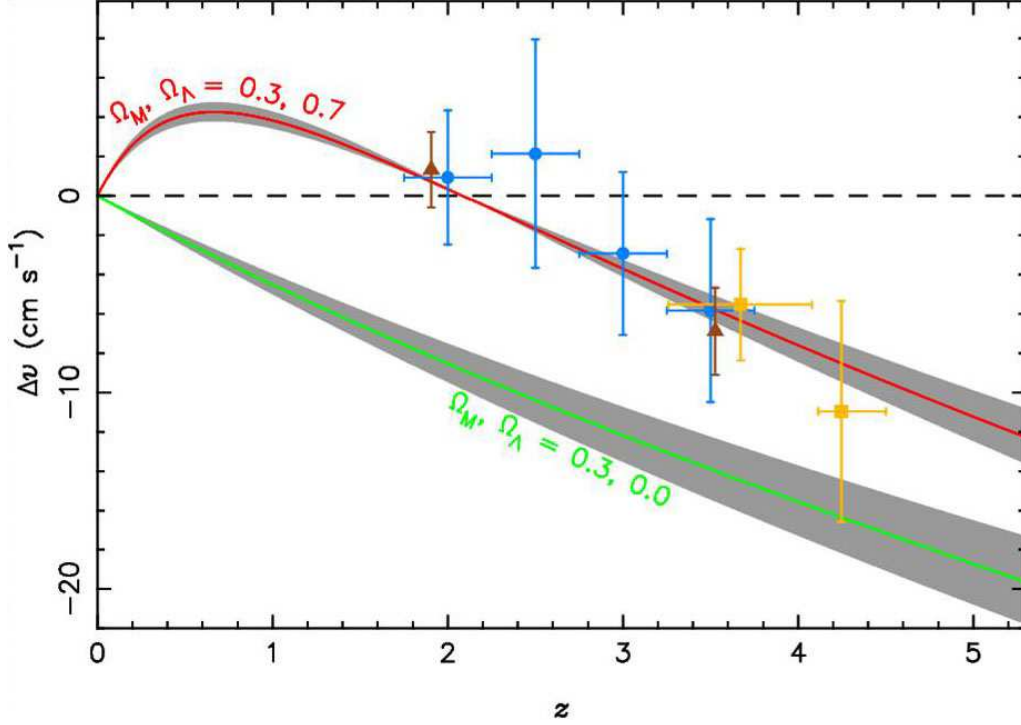


Fig. 3. – CODEX observing strategy assuming 2.2 nights/month of observation with a 42m ELT over 15 years. The three different sets of data points represent different implementations of the redshift drift experiment, each being optimal for a different goal: Blue points: 20 targets (in 4 bins), selected to give the highest overall radial velocity accuracy (2.13 cm/s). Yellow points: 10 targets selected to give the largest possible significance of a non-zero detection. Brown points: 2 targets, selected to give the best constraints on the acceleration and dark energy. The grey shaded areas around the curves correspond to the present  $H_0$  uncertainty of  $\pm 8$  km/s/Mpc.

formula:

$$(2) \quad \sigma_v = 2 \left( \frac{S/N}{2370} \right)^{-1} \left( \frac{N_{\text{epochs}} N_{\text{QSO}}}{60} \right)^{-\frac{1}{2}} \left( \frac{1+z_{\text{QSO}}}{5} \right)^{-1.7} \text{ cm/s}$$

where the last exponent changes to  $-0.9$  at  $z_{\text{QSO}} > 4$ , due to the crowding of features in the high-redshift Lyman forest. A resolution  $\mathcal{R} \geq 30000$  is sufficient to fully resolve the Lyman features. A higher resolution  $\mathcal{R} \sim 10^5$  would however be advisable in order to better identify metal lines in the spectra. Different observing strategies are being explored, according to different goals of the experiment (see Fig. 3) and it is reassuring to know that already today there are at least 20 known QSOs with redshift between 2 and 5 bright enough to achieve a radial velocity accuracy of 3 cm/s in 3200 hours of observation with a 42 m ELT.

Simulations have dictated the requirements for the spectrograph: a visible, high-resolution spectrograph with an exquisite long-term stability. To achieve this goal with an ELT is not trivial at all and requires an advanced design based on multiple modules (presently five are envisaged) based on R4 echelle gratings.

A long list of potential problems is being investigated, including secular changes in the structure of the IGM, the variability of the QSO continuum, weak lensing, the heliocentric correction, instrumental issues such as the guiding accuracy, temperature control and the scrambling of light in the fibers. None at the moment is recognized to be a show-stopper.

A special issue is represented by the wavelength calibration, because long-term stability is a must and serious doubts have been cast over the possibility to achieve the required accuracy with conventional lamps. This is the reason why a new concept is being developed: the laser frequency comb, an optical or near-IR laser generating a train of femtosecond pulses with the pulse repetition controlled by an atomic clock, producing a reference spectrum of evenly spaced  $\delta$  functions [8]

Of course an instrument like CODEX would have many other applications, among which it should be mentioned the variation of fundamental constants [3] to a precision of one part over  $10^8$ , or the detection of terrestrial extra-solar planets, in particular following-up earth-mass candidates discovered through other techniques, and Big Bang nucleosynthesis, with the determination of detailed primordial abundances in order to clarify some of the present tensions existing for example about isotopic ratios such as  ${}^6\text{Li}/{}^7\text{Li}$  [2].

Is the leap from HARPS on the ESO 3.6m telescope in La Silla to the E-ELT too daring? Maybe. This has prompted the CODEX Team to study the possibility of building a precursor, dubbed ESPRESSO (Echelle Spectrograph for PREcision Super Stable Observations) to be placed at the VLT, possibly at the incoherently combined focus of the four UTs. The instrument would look like one CODEX module and would allow the community to get a first glance of a significant part of the CODEX immediate science, of course with the exception of the cosmic dynamics. ESPRESSO would make it possible tests of the stability of the IGM that on the one hand are crucial for the CODEX feasibility and on the other hand would provide fundamental information on the formation of cosmic structures and feedback at high-redshift (see, for example [12]).

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